Solar System Ephemerides, Pulsar Timing, and Navigation

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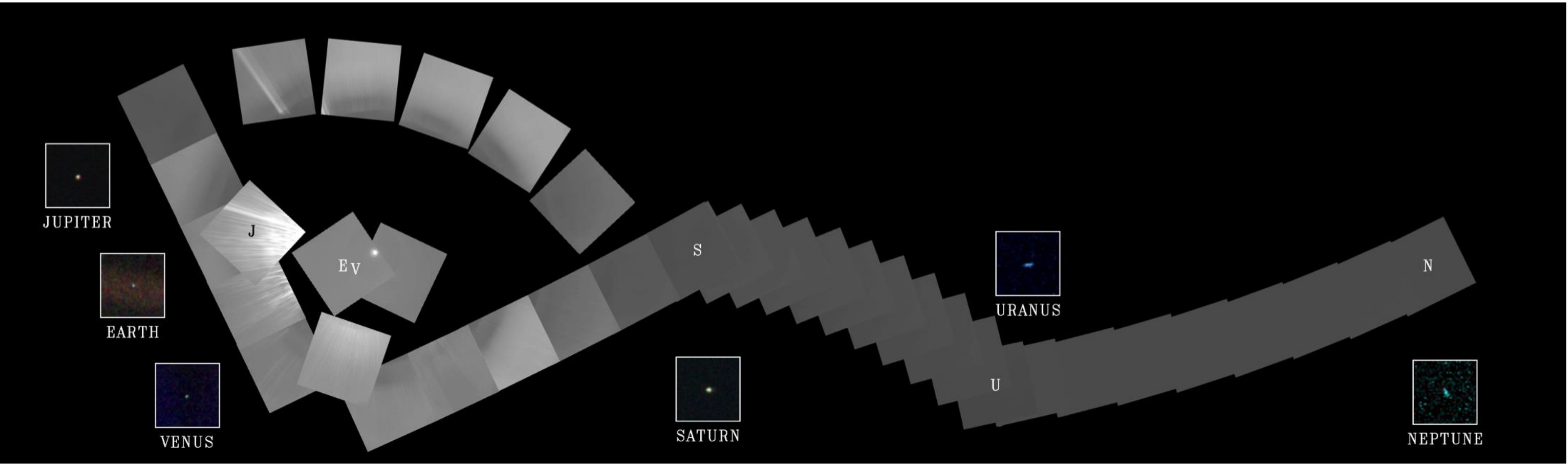
Part I: The Solar System Ephemeris

Voyager's Family Portrait

a.k.a. The Solar System



Voyager 1 spacecraft at edge of our solar system (1990 February 14)

- **Mars obscured by scattered light in camera ("rays of light")**
- **Mercury too close to the Sun**

Credit: NASA/JPL

Spacecraft Navigation

Objective: **Ensure spacecraft reaches required aimpoint**

Requirements:

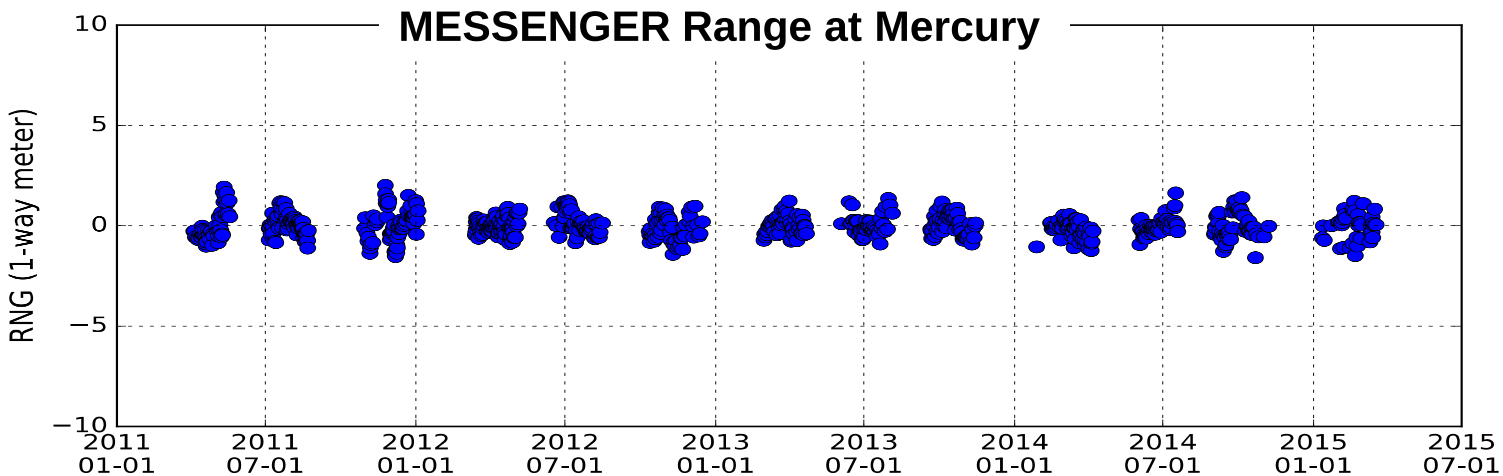
- **Mars landing: 100 m accuracy [top of atmosphere]**
  winds ~ 1 m/s
- **Other body landing: > 100 m accuracy (?)**
  Propulsion, terrain relative navigation
- **Orbit insertion: ≥ 1000 m accuracy**

B-plane is normal to approach trajectory

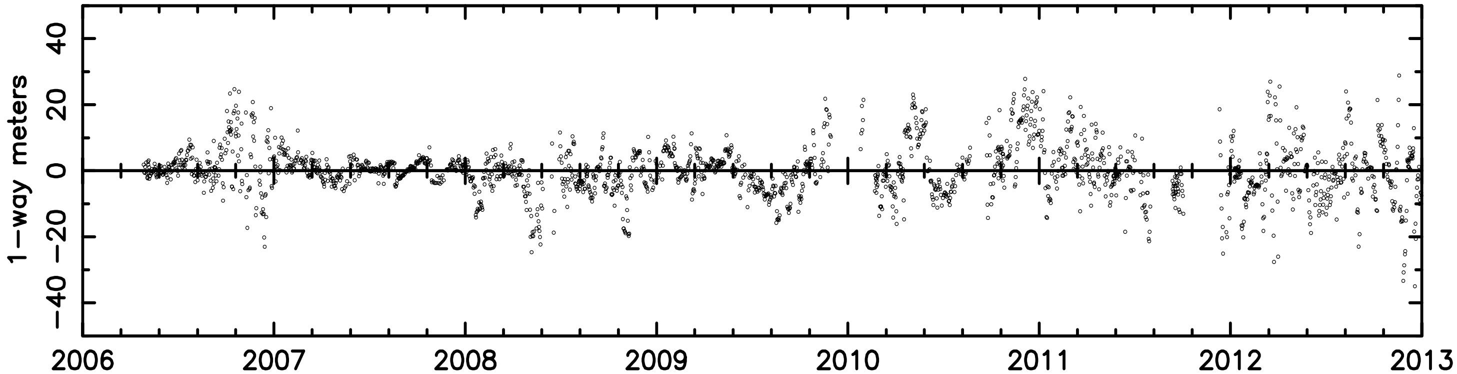
Aimpoint at top of Mars' atmosphere is targeted to ensure accurate landing on surface

➢ **Aimpoint = state vector: (x, y, z; v_x, v_y, v_z)**

Mercury and Venus Data



Venus Express Range



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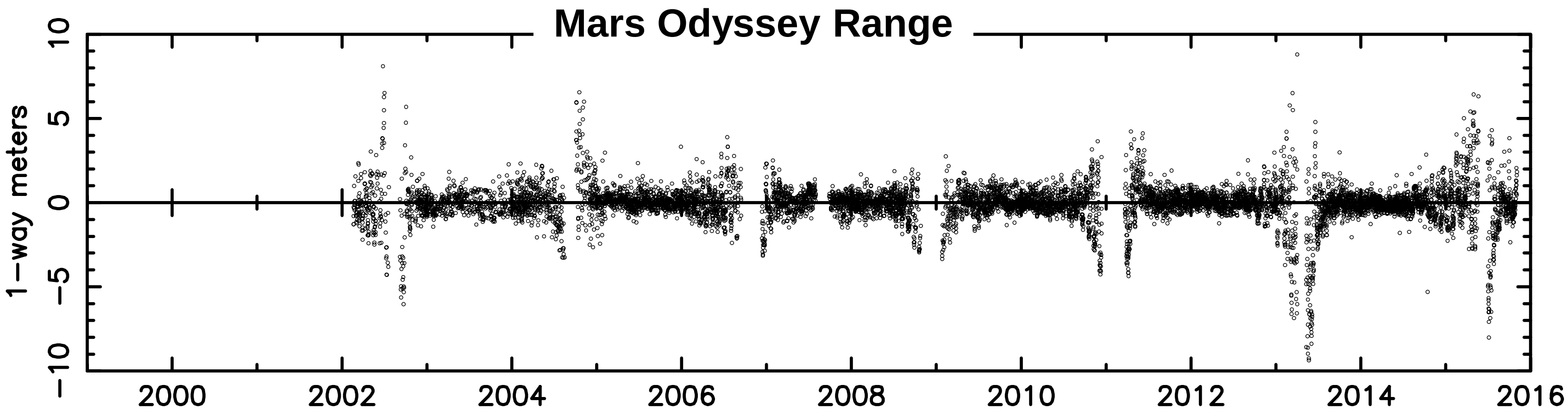
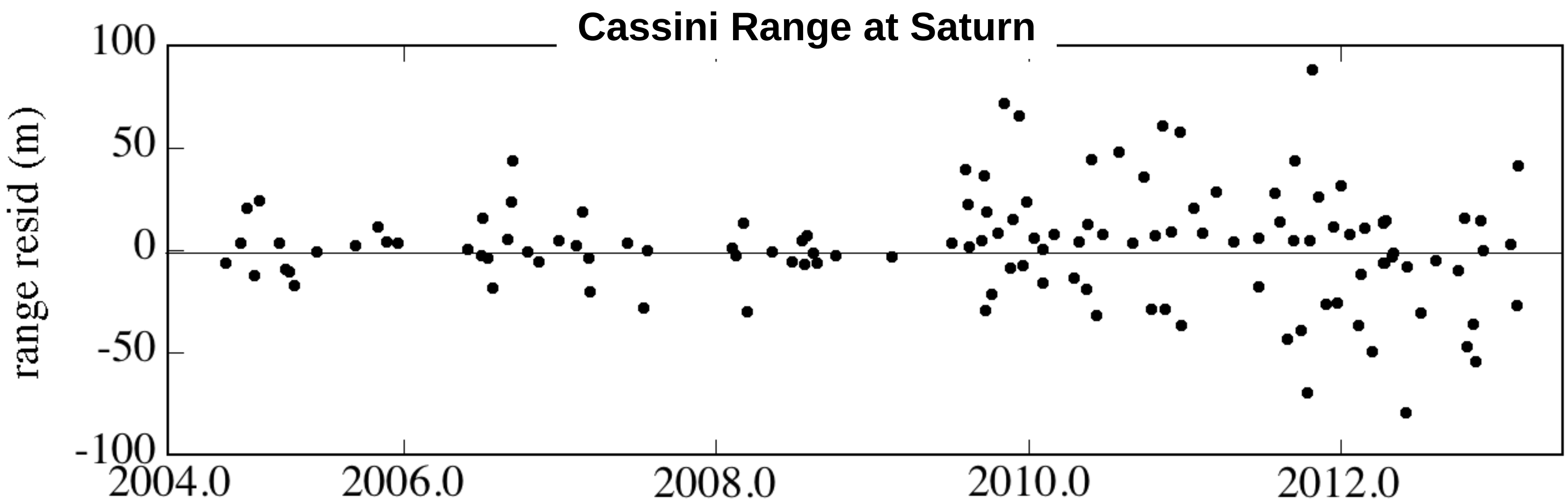
Mars and Saturn Range





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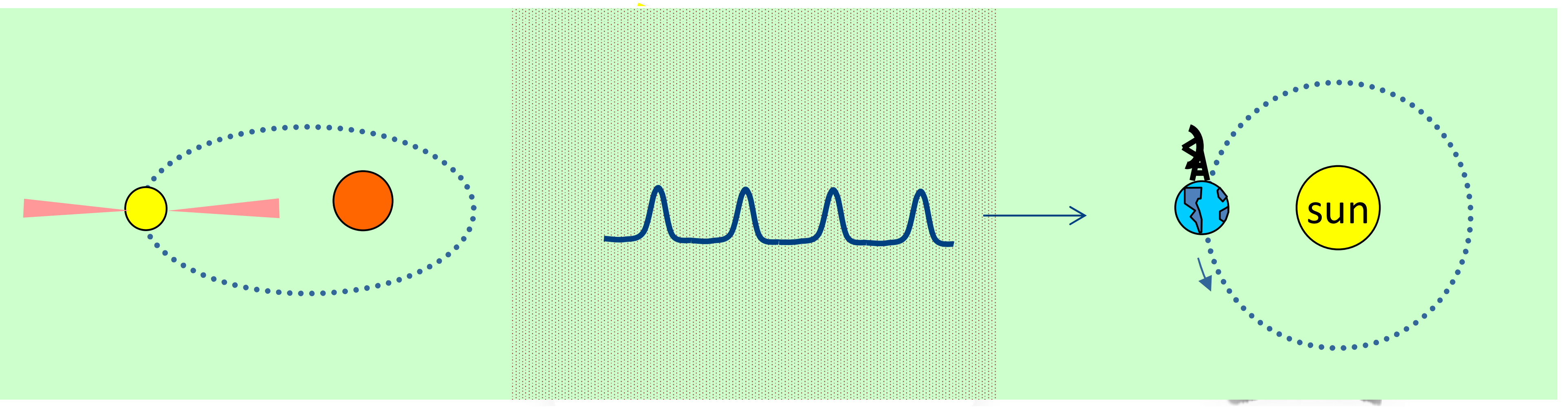
Part II: The Solar System Ephemeris and Pulsar Timing

Pulsar Timing and Solar System Ephemeris



$$t_{SSB} = t_{topo} + t_{corr} - D\mathrm{DM}/\nu^2 + \Delta_{R\odot} + \Delta_{S\odot} + \Delta_{E\odot}$$

Lorimer & Kramer, eqn. (8.6)

$$\Delta_{R\odot} = -\mathbf{r} \bullet \hat{\mathbf{s}}/c$$

Lorimer & Kramer, eqn. (8.7)

Solar System Ephemeris

What Do We Want?

$$\sigma_{TOA} = \sigma_{GWB} + \sigma_{SSB} + \sigma_{jitter} + \sigma_{\Delta DM} + \ldots + \sigma_{random}$$

$$\sigma_{GWB} \sim 10\ \text{ns}$$

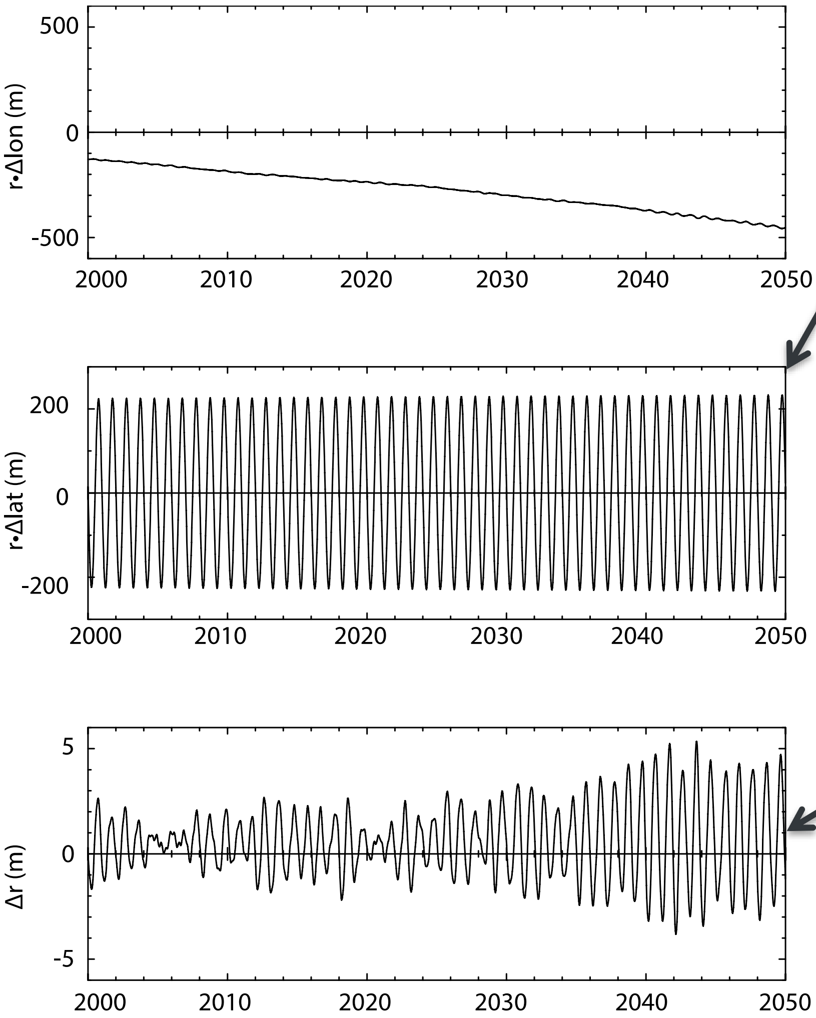
[reasonable expectation based on current astrophysics uncertainties]

$$\sigma_{SSB} \sim \sigma_{GWB}/3 \sim 3\ \text{ns} \sim 1\ \text{m}$$

[cf. 100 m ~ 300 ns]

- **See also S. Taylor's talk.**

Earth relative to Sun, DE421 – DE430



- **Change in ecliptic longitude at 2000.0 and variation in latitude reflect VLBI accuracy.**

  1 au*0.3 mas ~ 200 m

- **Earth-Sun distance stable to ~5 m**

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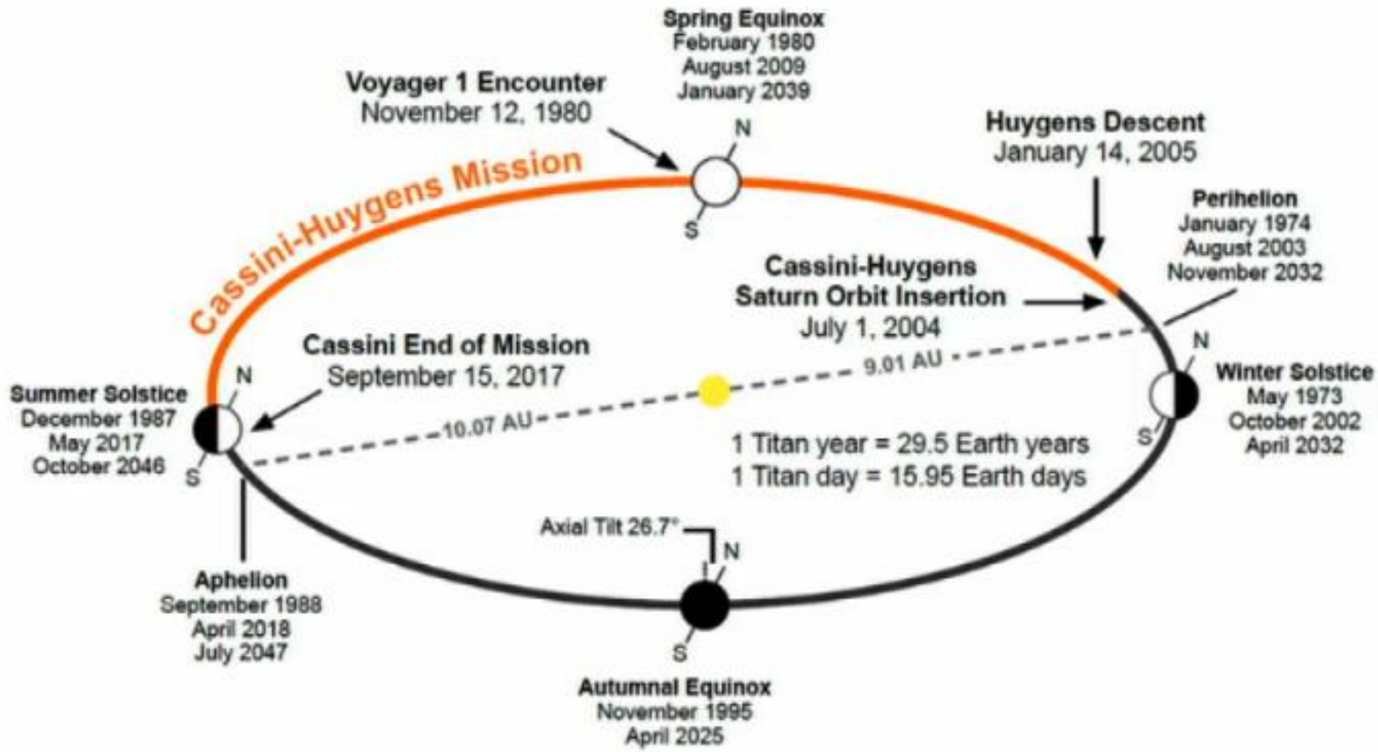
Outer Planets

Large Mass, Long Lever Arm, Little Data



cf. timing model for PSR J1024-0719

Hörst 2017

Spacecraft Navigation and Solar System Ephmeris

Objective: Ensure spacecraft reaches required aimpoint

Requirements

- **Mars landing: 100 m accuracy [top of atmosphere]**
  winds ~ 1 m/s
- **Other body landing: > 100 m accuracy (?)**
  Propulsion, terrain relative navigation
- **Orbit insertion: ≥ 1000 m accuracy**

➢ **Might know more later in August**

B-plane is normal to approach trajectory

Aimpoint at top of Mars' atmosphere is targeted to ensure accurate landing on surface

Pulsar Timing and Solar System Ephemeris

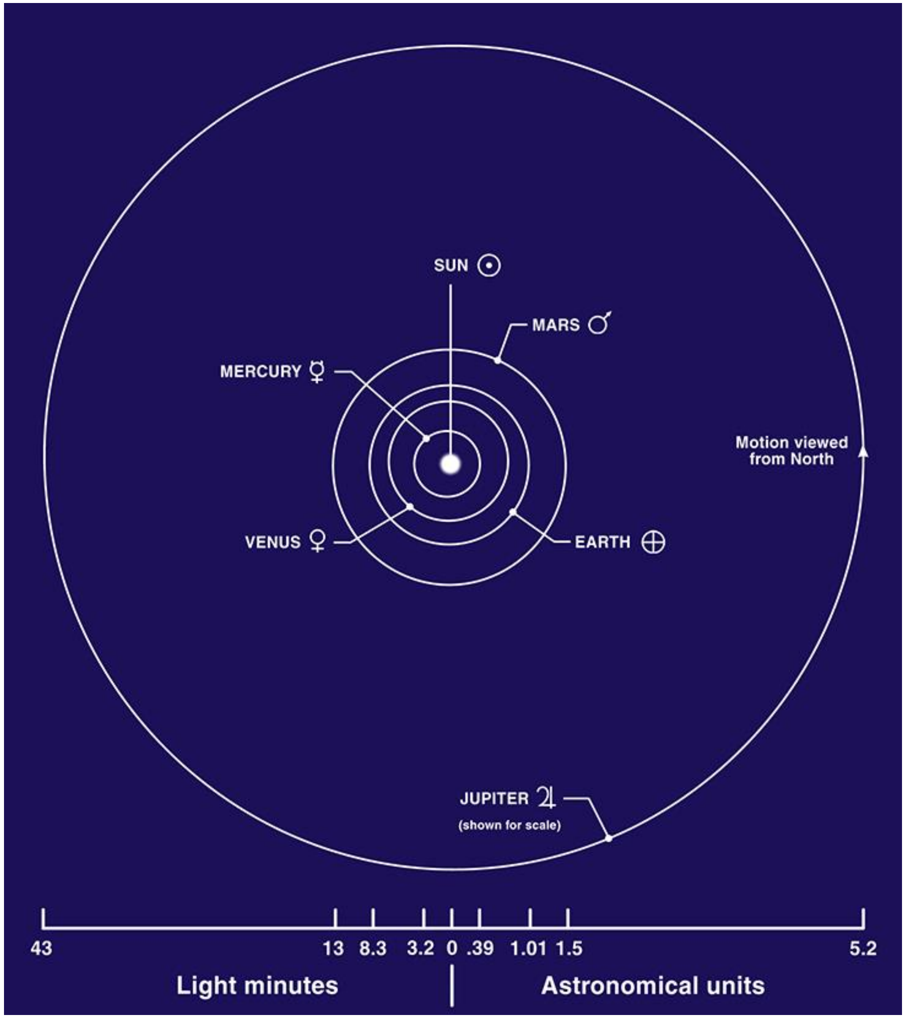
Or, Why Bother with the Spacecraft People?

Make a pulsar-based solar system ephemeris?

- **cf. IPTA solar system project**

Challenge: Enough good pulsars?

Best pulsars for constructing frame are best for GW study …



Part III: Navigation

Pulsar Navigation?

The Telecommunications and Data Acquisition Progress Report

TDA Progress Report 42-63 March and April 1981

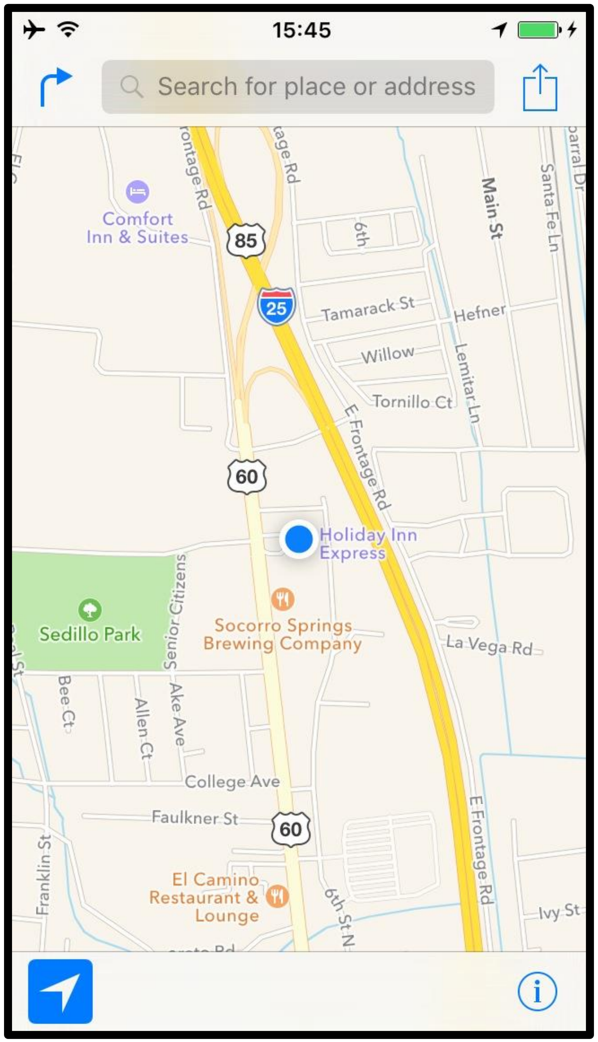
Navigation Using X-Ray Pulsars

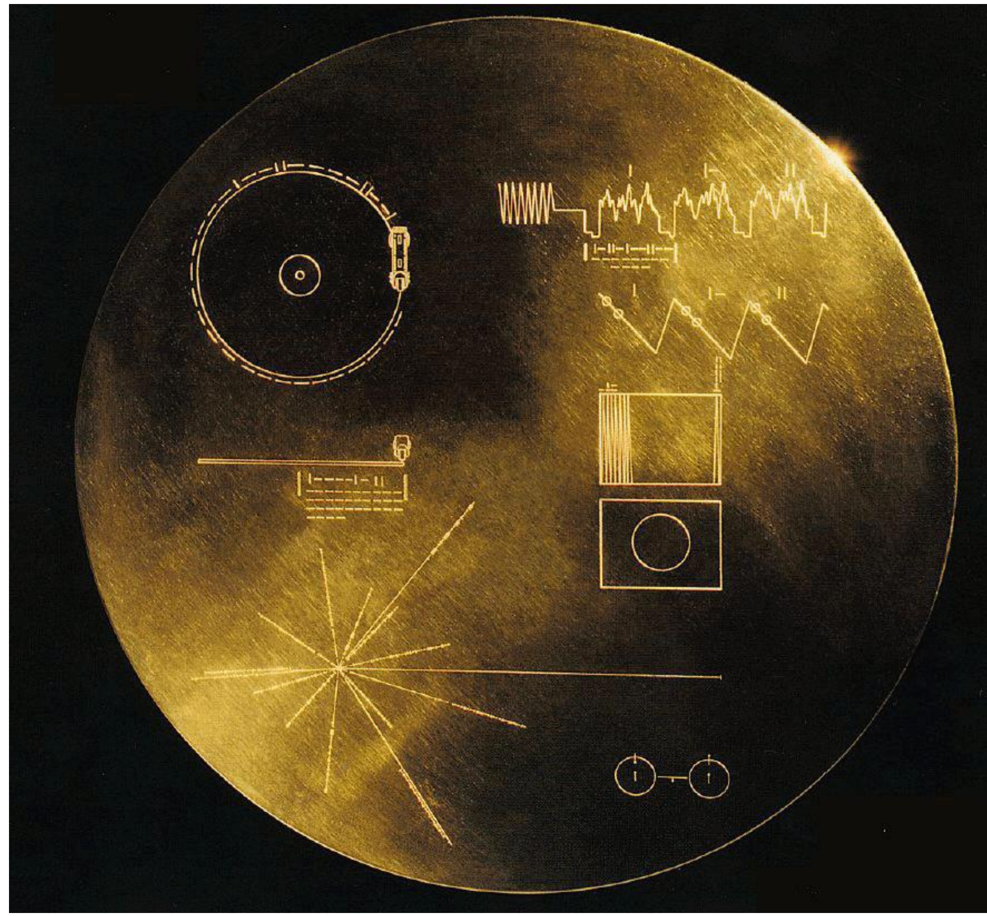
T. J. Chester and S. A. Butman
Communications Systems Research Section

Approximately one-dozen X-ray pulsars are presently known which emit strong stable pulses with periods of 0.7 to ~1000 s. By comparing the arrival times of these pulses at a spacecraft and at the Earth (via an Earth-orbiting satellite), a three-dimensional position of the spacecraft can be determined. One day of data from a small (~0.1 m^2) on-board X-ray detector yields a three-dimensional position accurate to ~150 km. This accuracy is independent of spacecraft distance from the Earth. Present techniques for determining the two spacecraft coordinates other than range measure angles and thus degrade with increasing spacecraft range. Thus navigation using X-ray pulsars will always be superior to present techniques in measuring these two coordinates for sufficiently distant spacecraft. At present, the break-even point occurs near the orbit of Jupiter. The Crab pulsar can also be used to obtain one transverse coordinate with an accuracy of ~20 km.

Position Determination vs. Navigation

"You Are Here" vs. "To Go From Point A to Point B"





Credit: NASA

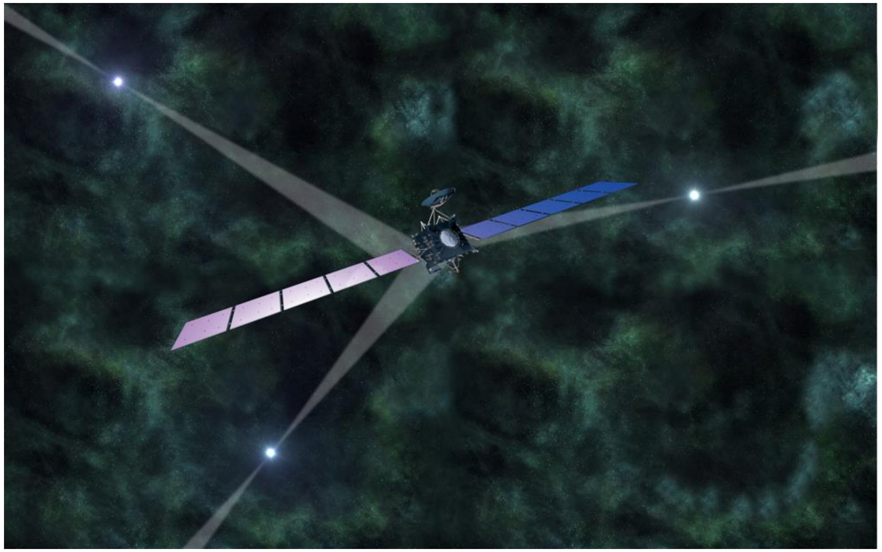
Deep Space Navigation and Position Determination

$\mathbf{r}_{PD} = f(t_{PD})$

$t_{PD} = t_{SSB} + t_{corr} - DDM/\nu^2 + \Delta_{R\odot} + \Delta_{S\odot} + \Delta_{E\odot}$

$\Delta_{R\odot} = -\mathbf{r} \bullet \hat{\mathbf{s}}/c$

Lorimer & Kramer



Credit: MPE/W. Becker; ESA

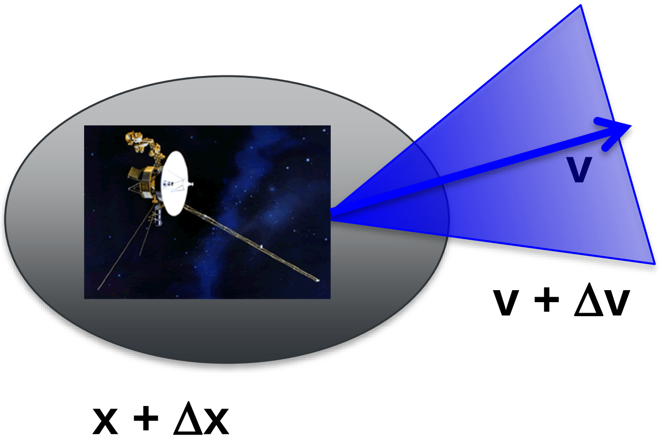
- **$\sigma_{PD} = f(\sigma_{SSB}; \ldots)$**

  $\sigma_{SSB} \sim 100$ m

  $\sigma_{PD} \propto \sigma_{SSB}/\sqrt{N}$?

- **$|v| \sim 30$ km/s**

Spacecraft Navigation



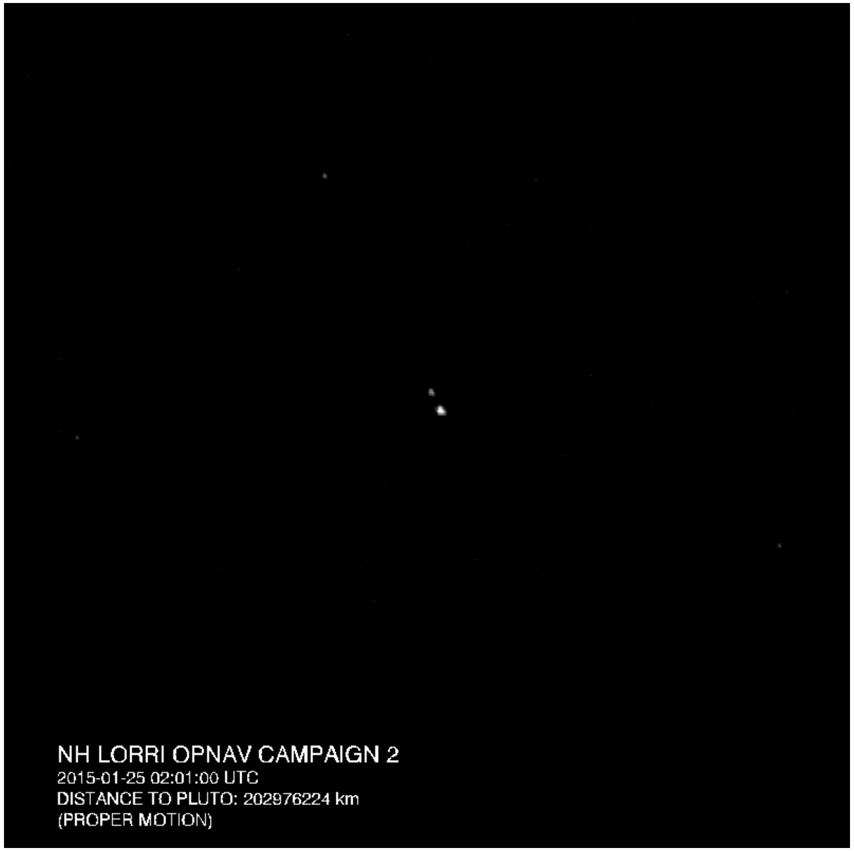
State-of-the-Art Navigation

Representative Values for General Context

- **Quiet interplanetary cruise: x ~ 10s km, v ~ few cm/s**
- **Delivery to Mars orbit insertion: ~10 km in B-plane (MRO)**
- **Delivery to Mars atmospheric entry: 0.21° in flight path angle (InSight)**
- **Mars orbit**
  - **0.5 × 20 × 5 m in RTN coordinates (MRO)**
  - **5 day prediction of 1.5 km downtrack, 28 day prediction of ~200 km downtrack (MRO)**
- **Jupiter orbit**
  - **Knowledge of 0.1 × 10 × 2 km (RTN) at perijove (Juno)**
  - **Delivery to Jupiter orbit insertion: ~100 km (Juno)**
- **Delivery to Titan flybys: < 1 km (*Cassini*)**
- **Delivery to Saturn icy moon flybys: < 2 km (*Cassini*)**
- **Delivery to Pluto flyby: ~100 km (NH Pluto)**
- **Small body orbit: < 50 m (Rosetta)**
- **Small body landing: < 25 m (OSIRIS-Rex)**

Optical Navigation

New Horizons approaching Pluto



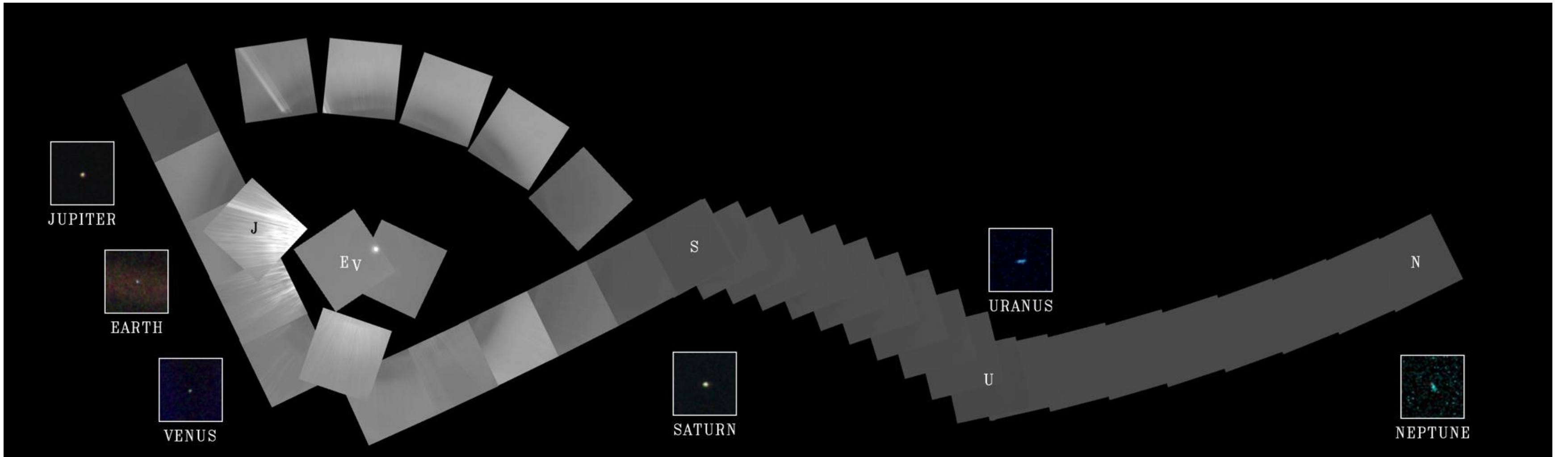
Credit: NASA/Johns Hopkins University Applied Physics Laboratory/Southwest Research Institute

~~*Cochrane* approaching TRAPPIST-1~~
Juno approaching Jupiter

Credit: NASA/JPL

Summary

- Solar system barycenter is critical element for pulsar timing and GW studies
- Little spacecraft navigation need for improved determination of barycenter (~ 100 m)
- GW study or barycenter determination? Probably cannot do both with current census
- Implications for pulsar-based position determination



Backup

Mars VLBI Data

Dominant Error Source